

Factorization and NLO QCD correction in $e^+e^- \rightarrow J/\psi(\psi(2S)) + \chi_{c0}$ at B Factories

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In nonrelativistic QCD (NRQCD), we study $e^+e^- \rightarrow J/\psi(\psi(2S)) + \chi_{c0}$ at B factories, where the P-wave state χ_{c0} is associated with an S-wave state J/ψ or $\psi(2S)$. In contrast to the failure of factorization in most cases involving P-wave states, e.g. in B decays, we find that factorization holds in this process at next to leading order (NLO) in α_s and leading order (LO) in v , where the associated S-wave state plays a crucial rule in canceling the infrared (IR) divergences. We also give some general analyses for factorization in various double charmonium production. The NLO corrections in $e^+e^- \rightarrow J/\psi(\psi(2S)) + \chi_{c0}$ at $\sqrt{s} = 10.6$ GeV are found to substantially enhance the cross sections by a factor of about 2.8; hence crucially reduce the large discrepancy between theory and experiment. With $m_c = 1.5\text{GeV}$ and $\mu = 2m_c$, the NLO cross sections are estimated to be 17.9(11.3) fb for $e^+e^- \rightarrow J/\psi(\psi(2S)) + \chi_{c0}$, which reach the lower bounds of experiment.

PACS numbers: 13.66.Bc, 12.38.Bx, 14.40.Gx

The production of double charmonium in e^+e^- annihilation at B factories [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] is one of the challenging problems in heavy quarkonium physics and NRQCD[16]. For $e^+e^- \rightarrow J/\psi\eta_c$ the QCD radiative correction has turned out to be essential to greatly enhance the theoretical prediction in NRQCD[17, 18]. However, the cross sections of other processes, i.e., $e^+e^- \rightarrow J/\psi(\psi(2S))\chi_{c0}$ measured by Belle[1]

$$\begin{aligned}\sigma[J/\psi + \chi_{c0}] \times B^{\chi_{c0}}[> 2] &= (16 \pm 5 \pm 4) \text{ fb}, \\ \sigma[\psi(2S) + \chi_{c0}] \times B^{\chi_{c0}}[> 2] &= (17 \pm 8 \pm 7) \text{ fb},\end{aligned}\quad (1)$$

are also larger than LO NRQCD predictions by about an order of magnitude or at least a factor of 5. Here $B^{\chi_{c0}}[> 2]$ is the branching fraction for the χ_{c0} decay into more than 2 charged tracks. Theoretically, two studies in NRQCD by Braaten and Lee[6] and by Liu, He, and Chao[7] showed that, at LO in the QCD coupling constant α_s and the charm quark relative velocity v , the cross-section of $e^+e^- \rightarrow J/\psi(\psi(2S))\chi_{c0}$ at $\sqrt{s} = 10.6\text{GeV}$ is only about $2.4 \sim 6.7(1.0 \sim 4.4)\text{fb}$ (depending on the used parameters, e.g., the long-distance matrix elements, m_c and α_s). So, it is crucial to verify that the QCD radiative correction can also greatly enhance $\sigma[J/\psi(\psi(2S))\chi_{c0}]$, before we can claim that the large discrepancy between theory and experiment for double charmonium production is really resolved.

However, we do need proof for the validation of factorization in exclusive production processes involving P-wave states at NLO in NRQCD. In fact, nonfactorizable infrared (IR) divergences are found in e.g. the P-wave charmonium production in B meson exclusive decays such as $B \rightarrow \chi_{c0}K$ [19], in contrast to the factorizable S-wave charmonium production in $B \rightarrow J/\psi(\eta_c)K$ [20], though the IR divergence in the P-wave case is m_c/m_b power suppressed[19]. This nonfactorizable feature for

the P-wave states is a quite general result and is essentially due to the non-vanishing relative momentum between the heavy quark and antiquark in P-wave states. So, differing from the double S-wave charmonium production, where factorization can be expected to generally hold at NLO in QCD, it is crucial to prove the validation of factorization in the special process $e^+e^- \rightarrow J/\psi(\psi(2S))\chi_{c0}$, where the P-wave charmonium is involved. Recently, the color transfer has been noticed[21] in associated heavy-quarkonium production, e.g., $e^+e^- \rightarrow J/\psi c\bar{c}$, where IR divergence appears due to soft interactions between the associated c (or \bar{c}) quark and the $c\bar{c}$ pair of charmonium, and hence breaks down factorization at NNLO. Therefore, it is significant to clarify related problems in QCD for $e^+e^- \rightarrow J/\psi(\psi(2S))\chi_{c0}$. Moreover, NLO QCD corrections are also important in understanding heavy quarkonium production at hadron colliders[22].

In this paper we will prove the validation of factorization for $e^+e^- \rightarrow J/\psi\chi_{c0}$ at NLO in QCD, and calculate the radiative corrections, while we have already found the NLO QCD corrections to $e^+e^- \rightarrow J/\psi\eta_c$ [17] and $e^+e^- \rightarrow J/\psi + c\bar{c}$ [23] to be large, and increase the cross sections by a factor of about 2. All these are at LO in v .

At LO in α_s , $J/\psi + \chi_{c0}$ can be produced at order $\alpha^2\alpha_s^2$, for which we refer to e.g. Ref [7]. The Feynman diagrams are shown in Fig. 1. Momenta for the involved particles are assigned as $e^-(k_1)e^+(k_2) \rightarrow J/\psi(2p_1) + \chi_{c0}(2p_2)$. In the calculation, we use **FeynArts** [24] to generate Feynman diagrams and amplitudes, **FeynCalc** [25] for the tensor reduction, and **LoopTools** [26] for the numerical evaluation of the infrared (IR)-safe one-loop integrals.

At NLO in α_s , there are ultraviolet(UV), IR, and Coulomb singularities. We choose renormalization schemes the same as in [17], and use $D = 4 - 2\epsilon$ dimension and relative velocity v to regularize IR and Coulomb

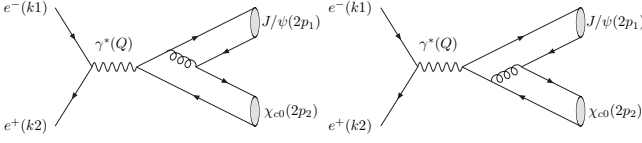


FIG. 1: Two of four Born diagrams for $e^- e^+ \rightarrow J/\psi \chi_{c0}$.

singularities. For the box diagrams shown in Fig. 2, Box N5, N8, N10 have IR and Coulomb singularities, Box N3 is IR finite, while the other nine diagrams have IR singularities. There are some scalar functions that should be calculated by hand, which are usually defined as

$$T_0^i[p_1 \dots p_{i-1}, m_0 \dots m_{i-1}] = \int \frac{\mu^{2\epsilon} d^D q / (2\pi)^D}{\prod_{l=0}^{i-1} [(q + p_l)^2 - m_l^2]},$$

where $p_0 = 0$, and $T^i = C, D, E$ for $i = 3, 4, 5$ respectively. Some of them were given in [17]. The others are

$$\begin{aligned} & \left. \frac{\partial E_0[p_2+q, p_1+p_2+q, 2p_1+p_2+q, q-p_2, 0, m, 0, m, m]}{\partial q^\alpha} \right|_{q=0} \\ &= \left\{ \frac{i}{24m^4 s^2 \pi^2} \left[4(5-2r)\sqrt{4-r} \log \left(\frac{2-\sqrt{4-r}}{\sqrt{4-r}+2} \right) + \right. \right. \\ & \quad \left. \left. (10+18 \log 2)r + (40-18r) \log \left(\frac{16}{r} \right) - \frac{192C_0}{s^3} \right] \right\} p_1^\alpha, \\ & \left. \frac{\partial D_0[p_2+q, p_1+p_2+q, q-p_2, 0, m, 0, m]}{\partial q^\alpha} \right|_{q=0} \\ &= \left[\frac{i(2+\log 4)}{m^2 \pi^2 s^2} - \frac{32C_0}{s^2} \right] p_1^\alpha, \\ & \left. \frac{\partial D_0[p_1, p_1+p_2+q, -p_1, 0, m, 0, m]}{\partial q^\alpha} \right|_{q=0} = \frac{ip_1^\alpha \log 4}{m^2 \pi^2 s^2} - \frac{32p_1^\alpha C_0}{s^2}. \end{aligned}$$

Here q is the relative momentum of charm quark in χ_{c0} , $r = 16m^2/s$, and C_0 is the Coulomb and IR divergent three point function $C_0[p_c, -p_{\bar{c}}, 0, m, m]$ [17],

$$C_0 = \frac{-i}{2m^2(4\pi)^2} \left(\frac{4\pi\mu^2}{m^2} \right)^\epsilon \Gamma(1+\epsilon) \left[\frac{1}{\epsilon} + \frac{\pi^2}{v} - 2 \right]. \quad (2)$$

The IR terms of BoxN5+N8+PentagonN10 are canceled by counter terms, and the Coulomb singularity is mapped into the wave functions. Other IR terms can be separated into three point functions $C_0[p_2+q, -p_1]$ and $C_0[p_2-q, -p_1]$ [27]. And we have

$$C_0[p_2+q, -p_1]|_{q=0} = C_0[p_2-q, -p_1]|_{q=0}, \quad (3)$$

$$\left. \frac{\partial C_0[p_2+q, -p_1]}{\partial q^\alpha} \right|_{q=0} = - \left. \frac{\partial C_0[p_2-q, -p_1]}{\partial q^\alpha} \right|_{q=0}. \quad (4)$$

Here $C_0[l', -l]$ means $C_0[l', -l, 0, m, m]$. Then we get that BoxN1+N4 and BoxN6+N7+PentagonN12 are IR finite. The IR terms of BoxN9+N2+PentagonN11 are canceled by vertex diagrams. The UV terms are canceled by counter terms. Then the final NLO result for

the cross section is UV-, IR-, and Coulomb-finite. Details of the calculation can be found in a forthcoming paper. Since the result is IR finite, $e^+ e^- \rightarrow J/\psi + \chi_{c0}$ is factorizable at NLO in NRQCD factorization.

The key part for the cancelation of IR divergence in our calculation is shown in Fig. 3. The IR term of the NLO vertex correction for two charm quarks of momenta p_1 and p_2+q shown in Fig. 3(a) is proportional to $p_1 \cdot (p_2+q)C_0[-p_1, p_2+q_1]$ (see also [21, 27] though the three-point function C_0 was not explicitly written there); while it is proportional to $-p_1 \cdot (p_2-q)C_0[-p_1, p_2-q]$ for a charm quark and an anti-charm quark of momentum p_1 and p_2-q as shown in Fig. 3(b). Then for the charm quark $c(p_1)$ associated with a colorless charm quark pair $c(p_2+q)\bar{c}(p_2-q)$, the IR term becomes

$$\begin{aligned} & \mathcal{M}_{NLO}^{IR} [c(p_1) + c(p_2+q)\bar{c}(p_2-q)] \\ & \propto (p_2+q) \cdot p_1 C_0[p_2+q, -p_1] - (p_2-q) \cdot p_1 C_0[p_2-q, -p_1] \\ & = 2q^\alpha \left[p_{1\alpha} C_0[p_2, -p_1] + p_2 \cdot p_1 \frac{\partial C_0[p_2+q, -p_1]}{\partial q^\alpha} \Big|_{q=0} \right] + \mathcal{O}(q^2), \quad (5) \end{aligned}$$

where it is expanded in powers of the relative momentum q at $q=0$. (The IR terms between $c(p_2+q)$ and $\bar{c}(p_2-q)$ or between $c(p_1)$ and $\bar{c}(p_1')$ are ignored since these $c\bar{c}$ pairs should evolve to bound states at large distances.)

Following implications can be found from Eq.(5):

(1) The IR term is finite when an associated charm quark connects with both legs of the S-wave state J/ψ , where $q=0$ can be taken at LO in v , and this corresponds to the zeroth order i.e. the vanishing $\mathcal{O}(q^0)$ term in Eq.(5).

(2) The IR term becomes divergent when the associated charm quark connects with both legs of the P-wave state χ_{c0} , where the relative momentum q has to be retained, and this corresponds to the first order i.e. the $\mathcal{O}(q^1)$ term in Eq.(5),

$$\mathcal{M}_{NLO}^{IR} \propto \frac{8q \cdot p_1}{s} \frac{\alpha_s}{\varepsilon_{IR}} \left[1 + \mathcal{O} \left(\frac{m^2}{s} \right) \right] + \mathcal{O}(q^2). \quad (6)$$

This nonvanishing IR divergence, which is actually independent of the associated quark flavor, is the origin for the non-factorizability in many processes involving P-wave states, e.g., in $B \rightarrow \chi_{c0} K$ decay [19], and also in B decays $B \rightarrow M_1 M_2$ with M_2 being an emitted P-wave light meson (f_0, a_1, b_1, \dots) [28] when the light meson mass e.g. m_{f_0}/m_B is not ignored in the IR divergent vertex corrections. In another words, factorization holds up only to terms that are m_q/m_b power suppressed.

(3) When the associated fermion is an anti-quark $\bar{c}(p_1)$, we can get a similar IR divergence by replacing p_1 with $-p_1$ in Eq.(5) and Eq.(6). Then by adding together the contributions of the associated charm pair $c(p_1)$ and $\bar{c}(p_1)$ connected with $c(p_2+q)\bar{c}(p_2-q)$, the IR divergence is canceled in the case of P-wave e.g. χ_{c0} . Note that since generally the associated quark pair $c(p_1)\bar{c}(p_1')$ has $p_1 \neq p_1'$ as shown in Fig. 3, the IR cancelation is incomplete and the

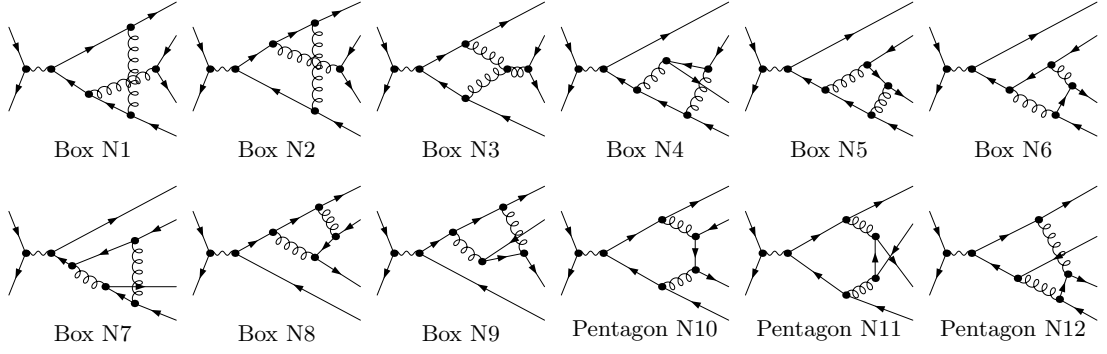


FIG. 2: Twelve of the twenty-four box and pentagon diagrams for $e^-(k_1)e^+(k_2) \rightarrow J/\psi(2p_1)\chi_{c0}(2p_2)$. Two upper charm legs are for J/ψ while two lower ones for χ_{c0} .

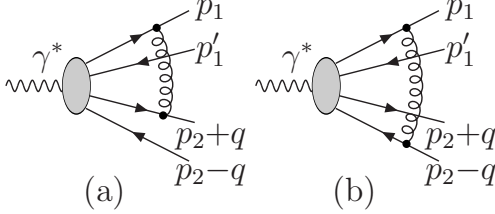


FIG. 3: Half of the diagrams for one-loop virtual IR corrections with two charm quark pairs $c(p_1)\bar{c}(p'_1)$ and $c(p_2+q)\bar{c}(p_2-q)$. The other two diagrams can be obtained by replacing $c(p_1)$ with $\bar{c}(p'_1)$.

divergence still remains. This means that factorization in $e^+e^- \rightarrow J/\psi\chi_{cJ}$ can hold at LO in v for the J/ψ (i.e. $p_1 = p'_1$) but not hold at NLO in v ($p_1 \neq p'_1$). Based on Eq.(5) we can draw a general conclusion that the double charmonium (including all S, P, D, \dots wave states) production in e^+e^- annihilation is factorizable at NLO in α_s only on condition that one of the double charmonium is an S-wave state in which the quark relative momentum is ignored. Or, factorization holds up only to terms that are m_c^2/s power suppressed. A similar conclusion is also obtained recently in a more general analysis for quarkonium production[29].

We now turn to numerical calculations for the cross sections of $e^+e^- \rightarrow J/\psi(\psi(2S))\chi_{c0}$. To be consistent with the NLO result the values of wave functions squared at the origin should be extracted from the leptonic width of $J/\psi(\psi(2S))$ and the two-photon width of χ_{c0} at NLO in α_s (see [16] and [30]), we obtain $|R_{1S}(0)|^2 = 1.01\text{GeV}^3$, $|R_{2S}(0)|^2 = 0.639\text{GeV}^3$, $|R'_{1P}(0)|^2 = 0.0575\text{GeV}^5$. Taking $m_{J/\psi} = m_{\psi(2S)} = m_{\chi_{c0}} = 2m$ at LO in v , $m = 1.5\text{ GeV}$, $\Lambda_{\overline{\text{MS}}}^{(4)} = 338\text{MeV}$, we find $\alpha_s(\mu) = 0.259$ for $\mu = 2m$, and get the cross sections at NLO in α_s

$$\begin{aligned} \sigma(e^+ + e^- \rightarrow J/\psi + \chi_{c0}) &= 17.9\text{fb}, \\ \sigma(e^+ + e^- \rightarrow \psi(2S) + \chi_{c0}) &= 11.3\text{fb}, \end{aligned} \quad (7)$$

which are a factor of 2.8 larger than the LO cross sec-

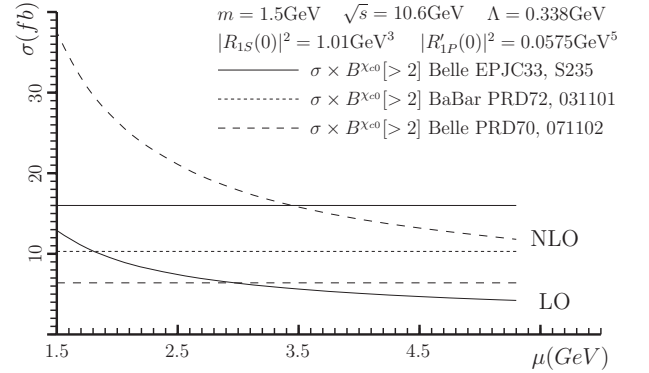


FIG. 4: Cross sections of $e^+e^- \rightarrow J/\psi + \chi_{c0}$ as functions of the renormalization scale μ .

tions $6.35(4.02)\text{ fb}$ for $J/\psi(\psi(2S))$. If we use the BLM scale[31], we get $\mu_{BLM} = 2.30\text{GeV}$, $\alpha_s = 0.291$, and the corresponding cross sections $8.02(5.08)\text{ fb}$ at LO and $22.8(14.4)\text{ fb}$ at NLO. Fig. 4 shows the cross sections at LO and NLO as functions of the renormalization scale μ , as compared with the Belle and BaBar data. Our LO and NLO results compared with experimental and other theoretical cross sections are shown in Table I. We see the NLO QCD correction enhances the cross sections by about a factor of 2.8, despite of existing theoretical uncertainties.

We emphasize again the crucial rule of the associated S-wave state J/ψ played in canceling the IR divergencies in the vertex corrections in $e^+e^- \rightarrow J/\psi\chi_{c0}$. At LO in v and NLO in α_s , the interaction of χ_{c0} with the charm quark (or antiquark) in the J/ψ is individually IR divergent, but the sum of that of the charm quark and antiquark in the J/ψ becomes IR finite. This result reflects the fact that the P-wave state χ_{c0} behaves as a color dipole, which interacts with the color charge carried by the charm quark (or antiquark) in the J/ψ , but the interactions vanish when the charm quark and antiquark in the J/ψ are combined into a colorless S-wave object at LO in v (see Eq.(5)). The validation of factorization

TABLE I: Experimental and theoretical cross sections of $e^+e^- \rightarrow J/\psi(\psi(2S))\chi_{c0}$ at B factories in units of fb. We use $|R_{1S}(0)|^2 = 1.01\text{GeV}^3$, $|R_{2S}(0)|^2 = 0.639\text{GeV}^3$, $|R'_{1P}(0)|^2 = 0.0575\text{GeV}^5$, $\Lambda = 0.338\text{GeV}$, $\sqrt{s} = 10.6\text{GeV}$, $m_c = 1.5\text{GeV}$, and $\mu = 2m_c$. The experimental data are the cross sections times the branching fraction for χ_{c0} decay into more than 2 charged tracks. But the Belle data of $\psi(2S) + \chi_{c0}$ in Ref.[3] correspond to χ_{c0} decay into at least 1 charged tracks.

	$J/\psi + \chi_{c0}$	$\psi(2S) + \chi_{c0}$
Belle $\sigma \times B^{\chi_{c0}}[> 2][1]$	$16 \pm 5 \pm 4$	$17 \pm 8 \pm 7$
Belle $\sigma \times B^{\chi_{c0}}[> 2(0)][3]$	$6.4 \pm 1.7 \pm 1.0$	$12.5 \pm 3.8 \pm 3.1$
BaBar $\sigma \times B^{\chi_{c0}}[> 2][4]$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	-
Braaten and Lee [6]	2.4	1.0
Liu, He and Chao [7]	6.7	4.4
Braguta et al. [9]	14.4	7.8
Our LO result	6.35	4.02
Our NLO result	17.9	11.3

at NLO for $e^+e^- \rightarrow J/\psi\chi_{c0}$ depends crucially on the associated S-wave state J/ψ .

In conclusion, we find that at NLO in α_s and LO in v , NRQCD factorization holds for the double charmonium production $e^+e^- \rightarrow J/\psi(\psi(2S))\chi_{c0}$. We get UV and IR finite corrections to the cross sections at $\sqrt{s} = 10.6\text{GeV}$, and the NLO QCD corrections can substantially enhance the cross sections with a K factor (the ratio of NLO to LO) of about 2.8; and hence it crucially reduces the large discrepancy between theory and experiment. With $m = 1.5\text{GeV}$ and $\mu = 2m$, the NLO cross sections are estimated to be 17.9(11.3) fb, which reach the lower bounds of experiment.

We thank G.T. Bodwin, Y. Jia, J.P. Ma and J.W. Qiu for helpful comments and discussions. This work was supported by the National Natural Science Foundation of China (No 10675003, No 10721063), and also by China Postdoctoral Science Foundation (No 20070420011).

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